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Advanced Adaptive Optics Technology Development

S. S. Olivier

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Advanced adaptive optics technology development

Scot S. Olivier*

Lawrence Livermore National Laboratory, P.O. Box 808, L-290, Livermore, CA 94551

ABSTRACT

The NSF Center for Adaptive Optics (CfAO) is supporting research on advanced adaptive optics technologies. CfAO research activities include development and characterization of micro-electro-mechanical systems (MEMS) deformable mirror (DM) technology, as well as development and characterization of high-resolution adaptive optics systems using liquid crystal (LC) spatial light modulator (SLM) technology. This paper presents an overview of the CfAO advanced adaptive optics technology development activities including current status and future plans.

Keywords: adaptive optics, wavefront control, MEMS, deformable mirror, liquid crystal, spatial light modulator

1. INTRODUCTION

1.1. NSF Center for Adaptive Optics

The NSF Science and Technology Center for Adaptive Optics (CfAO) was founded in November 1999, with Prof. Jerry Nelson as the Director. Headquartered at the University of California, Santa Cruz, the CfAO has 10 university nodes (UCSC, UC Berkeley, UCLA, UCSB, UC Irivine, Cal Tech, U. Chicago, U. Rochester, U. Houston, and Indiana U.) and 8 other U. S. observatory and laboratory partner institutions (NOAO, NSO, Gemini Telescope Project, W. M. Keck Observatory, LLNL, JPL, AFRL, and STScI). The CfAO also has several active industrial partners, including Lucent, Bausch & Lomb, LiteCycles and Boston Micromachines, and further industry partnerships are encouraged. Additional information can be found on the CfAO website at www.ucolick.org/~cfao.

The purpose of the CfAO is to advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education. The goal of the CfAO is to lead the revolution in AO, by developing and demonstrating the technology, creating major improvements in AO systems, and catalyzing advances nationwide within the next decade. The CfAO will pursue its purpose and achieve its goal by:

1) Demonstrating the power of AO by doing forefront science,
2) Increasing the accessibility of AO to the scientific community,
3) Developing and deploying highly capable AO systems and laser beacons,
4) Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations,
5) Integrating education with our research,
6) Building a Center community that is supportive of diversity through vigorous recruiting, retention, and training activities,
7) Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology,
8) Leveraging our efforts through industry partnerships and cross-disciplinary collaborations.

CfAO scientific research is currently concentrated in the areas of astronomy and vision science. Figure 1 shows telescopes with adaptive optics systems at two observatories associated with the CfAO. The 3-meter Shane telescope at Lick Observatory has the first and only currently operating sodium-layer laser guide star adaptive optics system [1-3]. The twin 10-meter telescopes at the Keck Observatory both have functioning adaptive optics systems, providing the highest resolution near-IR astronomical imaging. A sodium-layer guide star laser system is scheduled for installation on the Keck 2 telescope later this year [4]. Figure 2 shows the effect of adaptive optics on the quality of images looking into and out of the human

* Correspondence: email: olivier1@llnl.gov; phone: 925-423-6483; fax: 925-422-1796

eye. These images were taken using an adaptive optics system at the University of Rochester, which was the first to correct for high-order aberrations in the eye.

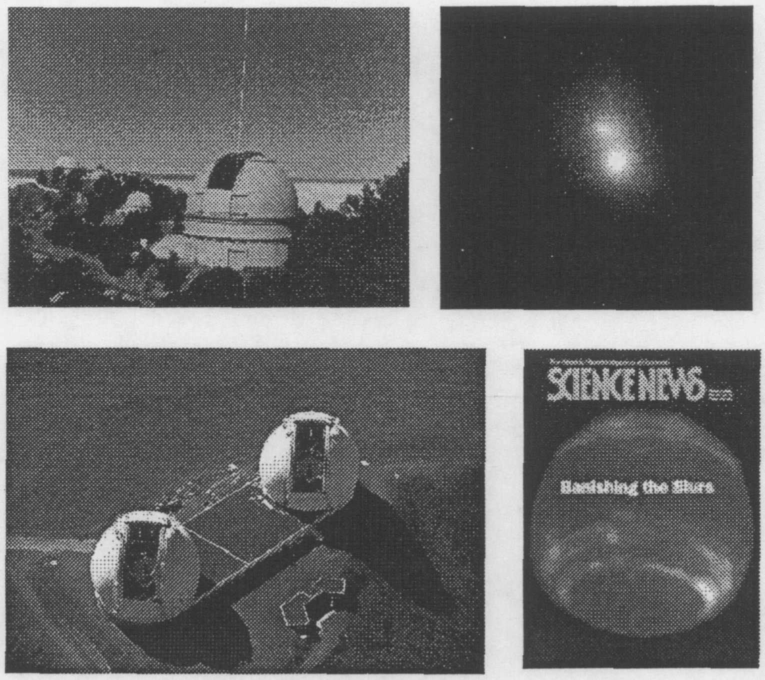

Figure 1 – Two astronomical observatories associated with the CfAO (Lick Observatory, top, and Keck Observatory, bottom), along with images obtained using their adaptive optics systems (an active galaxy image taken at Lick, top, and an image of Neptune taken at Keck shown on the cover of the March 4, 2000 issue of *Science News*, bottom).

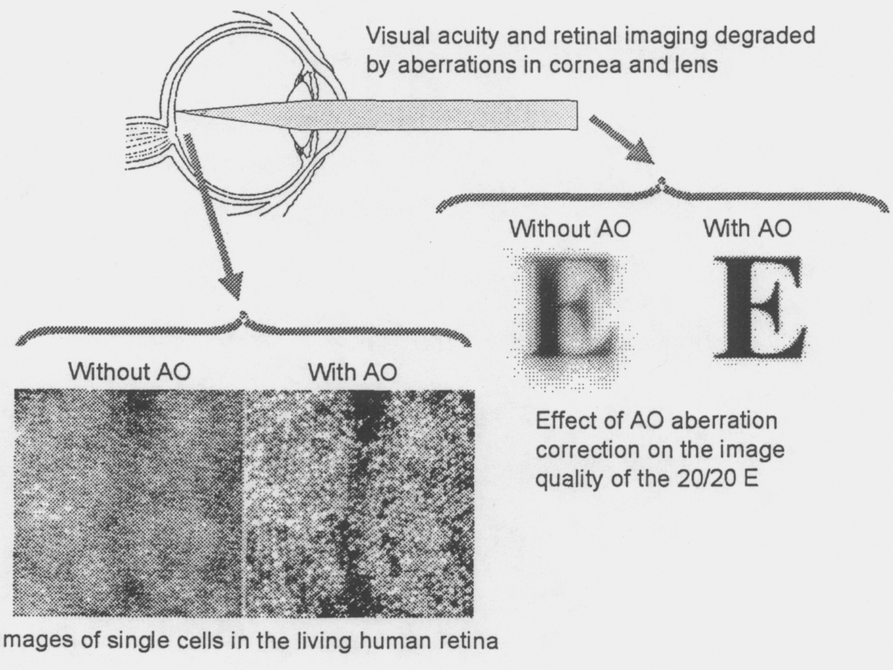

Figure 2 – Effects of adaptive optics on images looking into and out of the human eye. Data obtained with an adaptive optics system at the University of Rochester.

CfAO technology development is currently concentrated in the areas of astronomical guide star laser systems [5] and wavefront correction devices, including liquid crystal spatial light modulators and MEMS deformable mirrors. Figure 3 shows a MEMS deformable mirror (DM) system from Boston Micromachines and a liquid crystal spatial light modulator assembly from Hamamatsu. Both of these systems are being evaluated for adaptive optics applications by CfAO researchers.

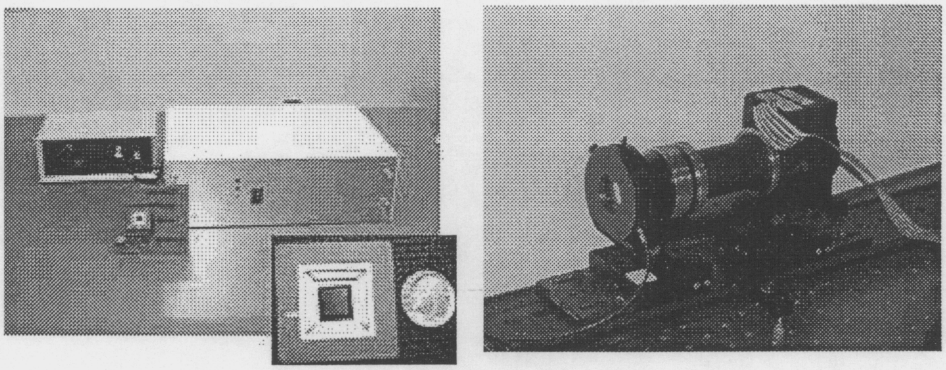

Figure 3 – MEMS deformable mirror system from Boston Micromachines (left) and liquid crystal spatial light modulator assembly from Hamamatsu (right). Both of these systems are being evaluated for adaptive optics applications by CfAO researchers.

1.2. Center for Adaptive Optics Themes

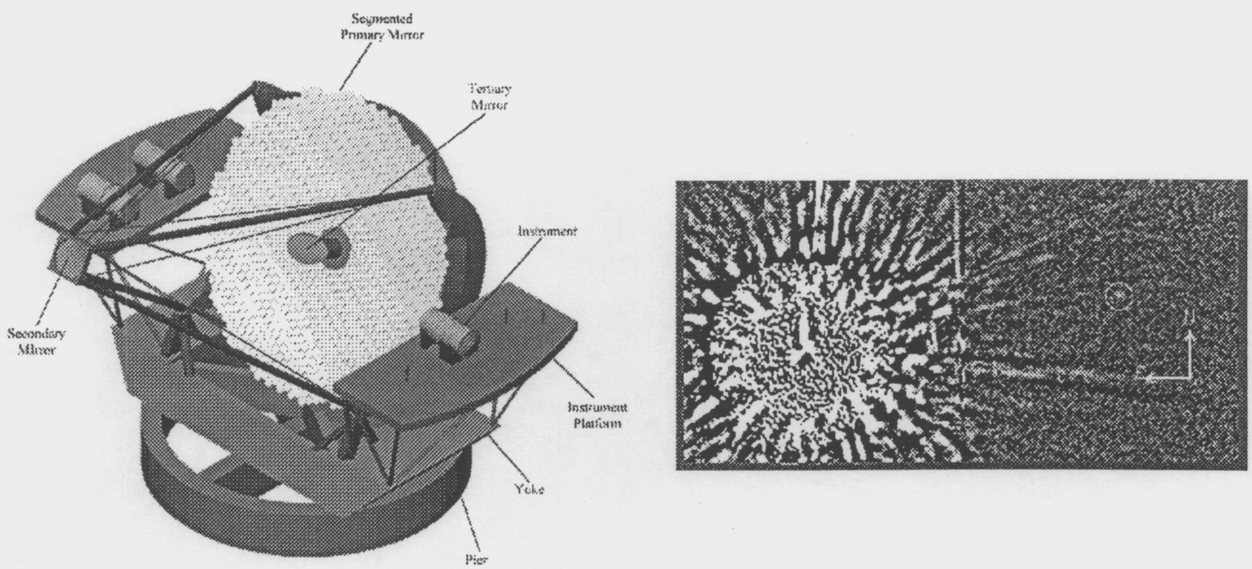

Figure 4 – A design concept for the 30-meter California Extremely Large Telescope (left) and a high-contrast image obtained with the AO system on the Keck II telescope (right) showing a dim object (circled) near a bright star. The two main CfAO themes in astronomy are AO for extremely large telescopes and eXtreme AO systems to enable ultra-high-contrast astronomical observations.

CfAO science and technology research is currently being organized into three main theme areas. Two of these themes are in the field of astronomy. The first theme is adaptive optics for extremely large telescopes. Figure 4 shows a design concept for the 30-meter California Extremely Large Telescope (CELT) that is being investigated by a joint University of California and Cal Tech team led by Prof. Jerry Nelson, who was also the project scientist for the Keck Telescopes. Adaptive optics for these extremely large telescopes may involve multi-conjugate adaptive optics such as the system currently being designed for the 8-meter Gemini South Telescope [6-9]. The second theme is eXtreme AO systems to enable ultra-high-contrast astronomical observations. Figure 4 also shows a high-contrast image of a dim object near a bright star obtained with the Keck 2 AO system. The brightness of the dim object is similar to that expected for a planetary companion of this young star, although this dim object is not confirmed to be physically associated with the this star (i.e., it may be a background star). The eXtreme AO theme seeks to extend the capability of AO systems for this type of observation beyond the current limits [10].

The third CfAO science and technology research theme is the field of vision science, specifically the development of compact ophthalmic instrumentation. Ophthalmic AO systems have been demonstrated in the laboratory for scientific research at the University of Rochester. The next horizon is to engineer compact, robust AO systems for use in clinics as well as scientific laboratories. The long-term goal is to commercialize compact AO systems for ophthalmic applications. Along the way, new and existing AO systems will be used to advance our understanding of human vision, and to explore biomedical applications of adaptive optics. Figure 5 shows several versions of commercial wavefront sensors along with a conventional phoropter, fundus camera and fundus image. By incorporating new compact wavefront corrector technologies, such as MEMS or LC SLM devices, along with the current generation of commercial wavefront sensing technology, it will be possible to extend the functionality of the fundus camera and phoropter to higher resolution, while maintaining a clinically viable instrument profile.

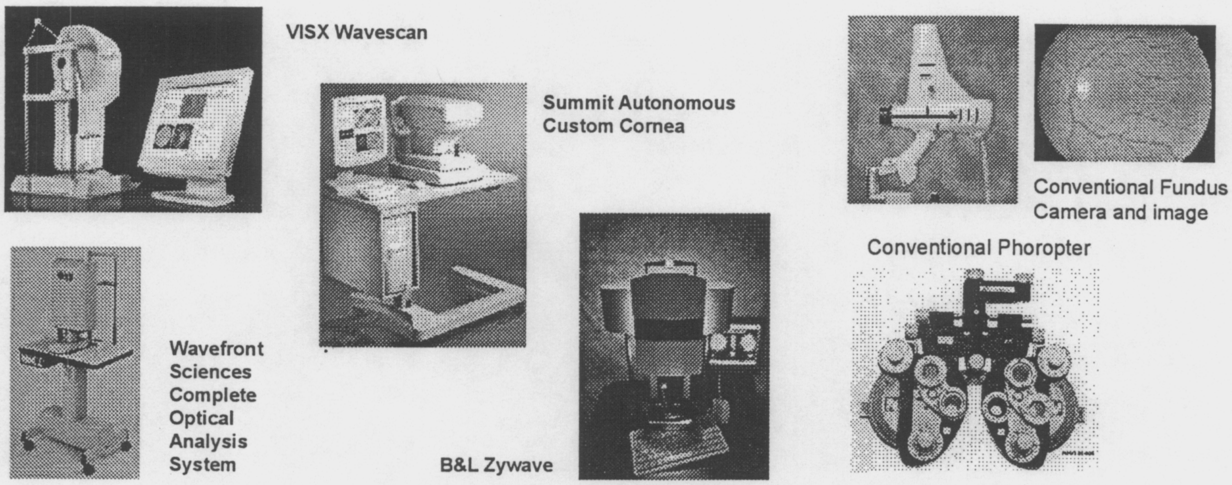

Figure 5 – Commercial ophthalmic wavefront sensing instruments (left) along with a conventional fundus camera and image (top right) and a conventional phoropter (bottom right). The main CfAO theme in vision science is the development of compact ophthalmic instrumentation using AO. The functionality of conventional ophthalmic instruments can be extended to higher resolution using AO. Maintaining a clinically viable instrument profile requires new compact wavefront corrector technology.

2. LIQUID CRYSTAL SPATIAL LIGHT MODULATOR SYSTEM DEVELOPMENT

The performance of the Hamamatsu optically addressed nematic liquid crystal spatial light modulator in an adaptive optics test bed at LLNL has been reported previously [11]. A corrected Strehl ratio of 0.76 was demonstrated at a wavelength of at 594 nm after closing the AO loop using a Hartmann wavefront sensor with 2000 subapertures. Based on these results, a system for ophthalmic application using this Hamamatsu SLM has been developed at LLNL [12]. This system, shown in Figure 6 will be used at the UC Davis Medical Center, in collaboration with researchers in the Dept. of Ophthalmology, to study the limits of human visual acuity. The vision science AO test bed at the U. of Rochester is also being retrofitted to test the Hamamatsu SLM in direct comparison with a conventional deformable mirror.

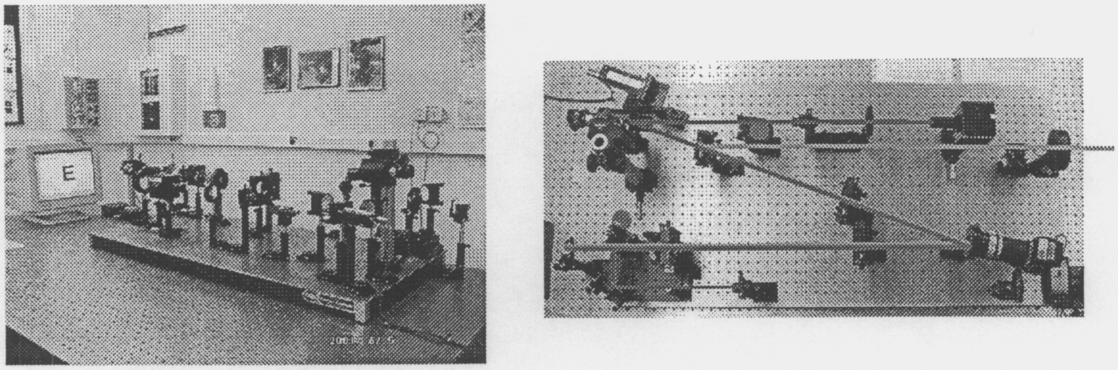

Figure 6 – AO system developed at LLNL for ophthalmic application using the Hamamatsu liquid crystal spatial light modulator. This system will be used at UC Davis for clinical tests of the limits of human visual acuity.

3. MEMS DEFORMABLE MIRROR DEVELOPMENT

3.1. Current CfAO MEMS Development

The CfAO MEMS development plan has been described previously [13]. During the first two years, this plan has included three microfabrication approaches, being pursued in parallel. The CfAO work has been leveraged from pre-existing programs at participating CfAO partner and collaborator institutions. The primary role of the CfAO has been to coordinate and focus these activities on specific technical goals relevant to the main CfAO research areas. Two electrostatically actuated devices, designed at the Air Force Research Laboratory (AFRL) [14] and Boston University (BU) [15], have been pursued. These designs utilize processes at the most established surface micro-machining foundries, Sandia National Laboratory (SNL) and Cronos/JDS Uniphase. The Berkeley Sensor & Actuator Center (BSAC) has been developing new designs and custom fabrication processes for next-generation devices with larger actuator stroke [16]. Packaging and drive electronics are being provided by Lucent Technologies, based on infrastructure from their optical cross-connect switching product, and by Boston Micromachines Corporation (BMC), a start-up company working with Boston University to commercialize their MEMS SLM device technology. LLNL has been acting to coordinate the efforts of the various groups, provide technical support, explore technologies for risk-reduction, and test devices.

3.1.1. BU MEMS Development

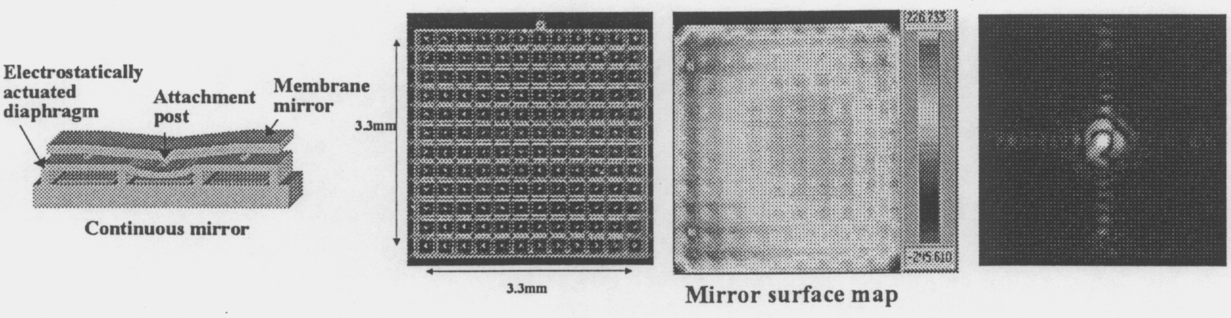

Figure 7 – Schematic (left), micrograph (middle left) and interferometric surface map (middle right) for MEMS deformable mirror designed by Boston University, along with far-field image from LLNL AO test bed. After active flattening of the MEMS deformable mirror, the interferometric surface map yielded <30 nm rms surface quality and the far-field spot had a measured Strehl ratio of >0.4 at 594 nm.

The development path based on the Boston University device design is currently beginning phase 2 with the design of a 1024 actuator device. In phase 1, devices with 140 actuators were packaged and integrated with drive electronics at Boston

Micromachines Corporation. The complete system, shown in Figure 3, was tested at LLNL. The design of the surface micromachined layer structure is specifically tailored to minimize print-through. A drawing of the device concept with a continuous surface membrane mirror is shown in Figure 7. Boston Micromachines and Boston University developed a simple post-processing technique based on ion processing to modify stress gradients in the surface membrane. After application of this technique, overall mirror surface quality of ~50 nm rms was obtained with the device in its relaxed state. An interferometric surface map of the device is shown in Figure 7, along with a dark-field micrograph looking through the surface membrane. After active flattening at LLNL, surface quality of ~30 nm rms was achieved. The mirror was also tested in the LLNL AO test bed. Far-field images were obtained through the system including the MEMS DM showing relatively good optical performance. A representative far-field image with a measured Strehl ratio of 0.43 at a wavelength of 594 nm is also shown in Figure 7. With the maximum allowed 240V applied to an actuator, 2 μm deflections have been achieved in tests at BU and LLNL. As part of the CfAO advanced AO technology development program, a BU/BMC micro-mirror assembly is currently being integrated into the U. of Rochester vision science AO test-bed. This device will be tested along with the LC SLM, and the performance will be compared to that achieved with the conventional deformable mirror.

In order to package and integrate drive electronics with the next-generation, 1024 actuator MEMS DM, capabilities and technologies developed at Lucent will be utilized. A 1024 channel drive electronics system has been provided to the CfAO based on the design for the drive electronics for the Lucent optical cross-connect switch. Several packaging tests have also been performed with BU devices at Lucent using their automatic wire bonding capability, and these activities will continue.

3.1.2. AFRL MEMS Development

The development path based on the AFRL device design has completed the fabrication stage at Sandia National Laboratory with a 252-element device. Fabricated devices have been tested at LLNL. A cutaway view of the device designed at AFRL and fabricated at SNL for CfAO is shown in Figure 8, along with measurements of the pixel surface quality showing ~50 nm deep trenches and dimples on the surface of the device, caused by print-through of the underlying structures. The actuation of the devices has also been tested and shown to yield 0.65 microns of stroke for 20 V input signal.

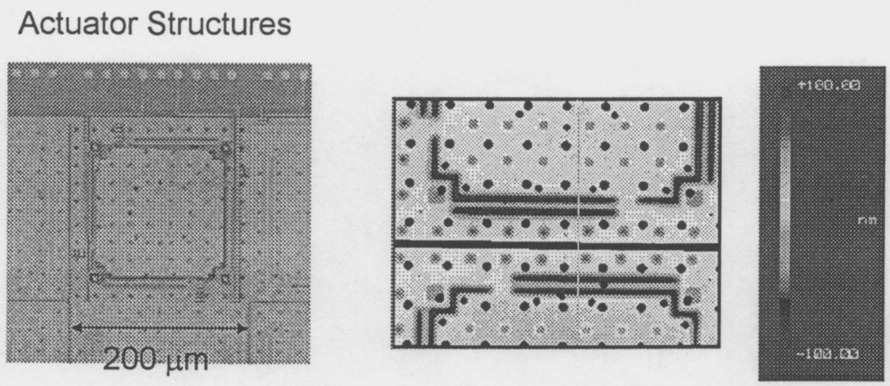

Figure 8 – Cutaway view of the MEMS SLM designed by the Air Force Research Laboratory and fabricated at Sandia National Laboratory for CfAO, and interferometric surface map of released mirror pixels showing ~50 nm deep trenches and dimples on the surface caused by print-through of underlying structures.

Based on these results, in comparison with those shown above for the devices designed at Boston University, further development of these devices is not currently being pursued by CfAO. However, the SNL fabrication process has been demonstrated to be a viable choice for surface micro-fabrication of MEMS SLM's with adequate optical surface quality, although further design work to minimize print-through would be advantageous. A limitation of this process is the relatively small achievable stroke, limited by the process layers' thickness. Devices designed at Boston University and fabricated in a custom process at JDS Unphase/Cronos have a stroke that is ~3 times larger, which increases their utility for applications in astronomy and vision science, although the voltage requirement to achieve this stroke is substantially higher. In addition, the BU devices have been designed and fabricated with a continuous surface, which also improves their utility for these applications.

3.1.3. BSAC MEMS Development

The development path at BSAC has resulted in the design, construction and measurement of an array of 7 mirror support pixels that are elevated roughly 20 μm above the wafer surface by the action of bimorph flexures. Figure 9 shows micrographs of the 7 mirror support pixels and a single-crystal silicon mirror substrate bonded to one of the mirror support pixels by a fluidic self assembly technique developed at BSAC [17]. The hexagonal pixels can be actuated by electrostatic forces applied using three under-electrodes to provide piston and tip/tilt motions. BSAC has demonstrated a new fabrication procedure to produce optically flat mirror surfaces and shown that they remain optically flat when actuated, using a Berkeley-developed interferometric, stroboscopic system. The pixel surface variations are measured to be smaller than 30 nm peak-to-valley, as shown in the interferometric surface map in Figure 9.

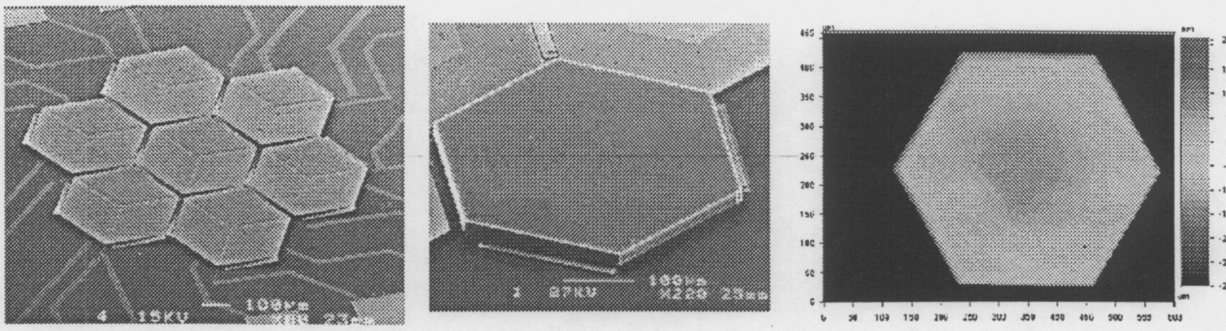

Figure 9 – Micrographs of 7 mirror support pixels designed and fabricated at BSAC (left) and single-crystal silicon mirror substrate bonded to mirror support pixel using BSAC self-assembly technique (middle). The interferometric surface map (right) shows a surface quality of 5.3 nm rms.

3.2. Future CfAO MEMS Development

The CfAO begins its third year in November 2001. One of the primary technology development goals for the CfAO in its third year is to continue to coordinate and support research on MEMS DM devices that will satisfy the requirements for a commercial clinical ophthalmic AO system. Several new development activities show promise for advancing the state of the art in this area. First, BU has designed a 1024-actuator continuous device, which will be fabricated at JDS Uniphase/Cronos later this year. A preliminary prototype of this design is shown in Figure 10.

Of potentially more importance for the application to vision, BSAC will continue to develop its high-stroke device mirror arrays. A redesign of these micro-mirrors is now underway to produce arrays with fabrication that makes use only of batch-processing steps, which will allow scaling of the arrays to the number of mirrors (~100) necessary for the vision science application. BSAC is also working to produce mirrors with piston motions up to 12 μm.

Figure 10 also shows a schematic of the concept for a MEMS DM designed at Stanford University [18,19]. This design uses bulk micro-machining as opposed to surface micro-machining to produce a continuous-surface device. The mirror is fabricated by combining two separate pieces. The top piece is formed by etching a wafer of single crystal silicon, leaving a 10 μm thick continuous membrane on the top and a 10 μm semi-continuous membrane on the bottom. During the etching process, pillars of silicon are formed connecting the upper mirror membrane and the lower interstitial membrane. Recessed electrodes are formed in another silicon wafer to apply the electrostatic force to the interstitial membrane. To complete the fabrication, the two pieces are bonded together with epoxy. Prototype devices fabricated at Stanford based on this design have been demonstrated with a surface quality of <30 nm rms over the entire clear aperture. Figure 10 also shows an interferogram of a prototype Stanford deformable mirror demonstrating the surface quality. The next steps required to extend the functionality of this device for application to vision science, are (1) to increase the number of actuators by an order of magnitude, from ~25 to ~250, and (2) to develop methods to increase the actuator stroke by an order of magnitude, from ~1 μm to ~10 μm. We plan to carry out these investigations in collaboration with Stanford and a spin-off company, Intellite, as part of the CfAO MEMS program and through a new MEMS development project described below.

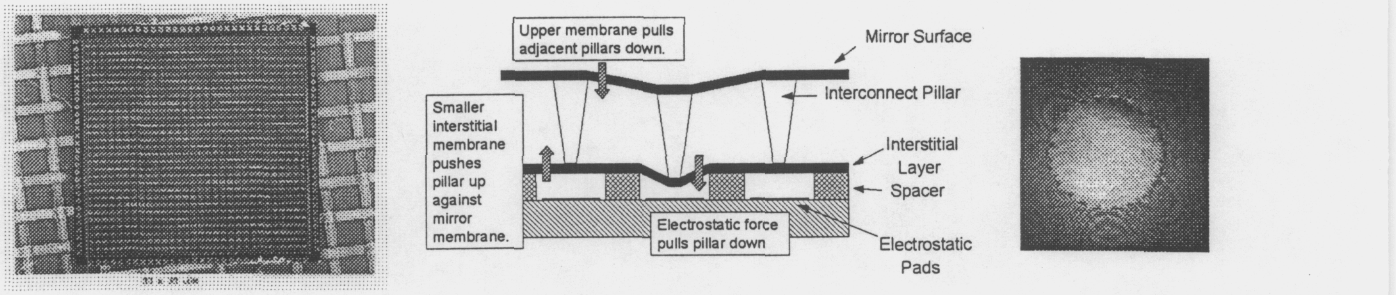

Figure 10 – New MEMS deformable mirror technologies: prototype Boston University 1000-actuator MEMS deformable mirror (left), schematic design of Stanford University MEMS deformable mirror (middle), and interferogram of prototype Stanford deformable mirror with <30 nm rms surface quality (right).

In addition to these activities, both Lucent and JPL will also be investigating new techniques in the design of MEMS DM's to enable high stroke appropriate for the vision application. Lucent will investigate new membrane mirror technologies, while JPL will investigate micromachined piezo-electric structures.

3.3. Related MEMS SLM Development

CfAO applications in the two main astronomical themes require wavefront corrector technologies with more than one thousand phase control points. In order to go beyond 1024 elements in a MEMS deformable mirror, new process approaches may be required. The scaling limitation for the pure surface micromachining approaches is due to the necessity of making electrical connection to each pixel by means of a wire that must be run out to the edge of the device through one of a small number of available layers. These wires terminate in a bond pad to which another set of wires must be connected leading to the drive electronics located off-chip. While this topology is feasible for a 32×32 device, it becomes impractical for much larger devices. The solution is to integrate the drive electronics with the MEMS SLM device so that the drive circuitry is situated beneath each pixel and any required electrical connections between the drive circuit and the SLM pixel are made from the back of the SLM.

There are two general methods to accomplish the integration between the SLM and drive circuitry. The first method is to fabricate the MEMS SLM device and the drive electronics in two separate chips and then use a chip bonding technique to bring the two devices together. A similar approach is used, for example, in the fabrication of infra-red detector arrays by the Rockwell Science Center, which uses an indium bump bonding technology to reliably make electrical connection between millions of array elements and amplifier circuits. The second integration method is to fabricate the MEMS SLM directly on top of the drive circuitry. This approach has been used, for example, by Texas Instruments in the fabrication of the Digital Micromirror Device, which has been produced with over two million pixels. Boston University and Boston Micromachines Corporation have developed a conceptual design based on the latter approach. Stanford University and BU/BMC working with LLNL, Lucent, Georgia Tech and a spin-off company from the Berkeley Sensor and Actuator Center, MicroAssembly Technolgy, have developed conceptual designs based on the former approach. A conceptual drawing of this approach is shown in Figure 11.

LLNL has obtained funding from DARPA to develop these approaches in collaboration with these groups to enable new applications in communications, imaging and targeting. By correcting for the effects of atmospheric turbulence and aberrations in lightweight optics, these MEMS SLM's can provide compensated optical communications [20], imaging and targeting for a variety of DOD scenarios. While the particular MEMS devices being developed for the DARPA project may not be optimal for vision science or astronomy applications, the packing and drive electronics approaches will be adaptable to MEMS deformable mirrors that are well suited to these applications. Integration of drive electronics and MEMS devices will support vision AO by enabling very compact, inexpensive devices suitable for clinical systems. In particular, the cost of MEMS deformable mirrors could drop from >$10 per channel with current off-chip electronics, to <$1 per channel with integrated electronics. We plan to investigate how to best leverage the technology being developed for this DARPA project, to produce high-order deformable mirrors for vision and astronomy applications. In addition, the BSAC development effort supported directly through the CfAO is also investigating the electronics integration issue using new process technology for silicon and germanium that has process temperatures compatible with CMOS electronics.

LLNL is also leading an NRO project to demonstrate designs and MEMS fabrication processes applicable to the production of large, high-order deformable mirrors suitable for correcting optical aberrations in lightweight space telescopes. This project is being carried out in collaboration with Intellite, a spin-off company from Stanford University. We will also investigate how to leverage the technologies developed for this project to produce high-order deformable mirrors for vision and astronomy applications. In particular, the NRO application requires large surface motions consistent with requirements for vision AO.

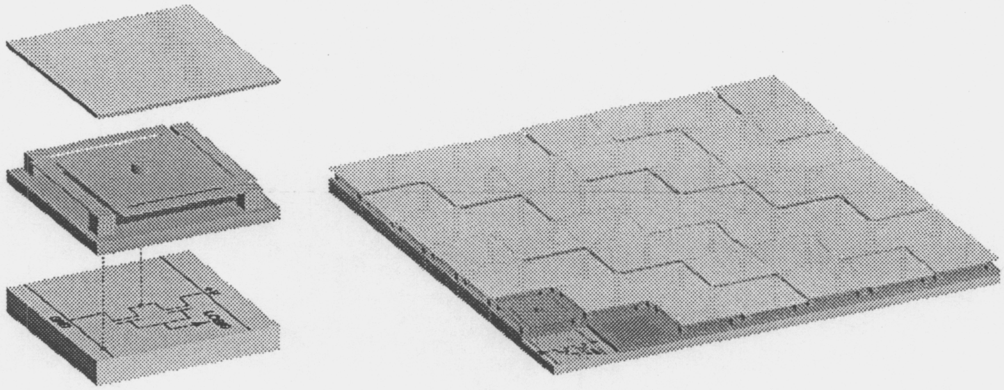

Figure 11 – Conceptual drawing of a MEMS SLM assembled by modular integration of separate mirror elements, micromachined actuators, and drive circuitry that are bonded together.

4. CONCLUSIONS

Based in part on previous work at LLNL, the Hamamatsu LC SLM has been shown to have promise for high-resolution wavefront control for scenarios with linearly polarized light, and fixed or slowly varying wavefront aberrations with either <1 wave peak-to-valley deviation or using phase wrapping in a narrow spectral band. The CfAO is pursuing the use of LC SLM devices for application to high-resolution wavefront control for vision science.

MEMS DM technology has achieved the surface quality necessary for wavefront control applications. New optical MEMS device development for wavefront control will lead to new levels of integration for MEMS mirror arrays. Complete integration could lower the cost of functional optical MEMS devices to less than one dollar per channel. Low cost MEMS wavefront correctors have application to astronomy, ophthalmology and laser communications and imaging. The CfAO, with significant leveraging from pre-existing and new programs, is pursuing multiple paths to achieve these goals.

ACKNOWLEDGEMENTS

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